Optical patterning of magnetic domains and defects in ferromagnetic liquid crystal colloids

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(Recei ed 18 J l 2015; accep ed 3 A g 2015; p bli hed online 20 A g 2015)

A promi ing approach in de igning compo i e ma erial i h an n al ph ical beha ior combine olid nano r c re and orien a ionall ordered of ma er a he me o cale. S ch compo i e can no onl inheri proper ie of heir con i en b al o can e hibi emergen beha ior ch a ferromagne ic ordering of colloidal me al nanopar icle forming me o copic magne i a ion domain hen di per ed in a nema ic liq id cr al. Here, e demon ra e he op ical pa erning of domain r c re and opological defec in ch ferromagne ic liq id cr al colloid , hich allo for al ering heir re pon e o magne ic eld . O r nding re eal he na re of he defec in hi of ma er em hich i differen a compared o non-polar nema ic and ferromagne alike. [h p://d .doi.org/10.1063/1.4928552]

Liq id cr al (LC) colloid a rac a con iderable amo n of cien i c in ere dri en b he richne of heir ill mina ion, 95 μl of pen lc anobiphen l (5CB, Cheng hi Yongh a Dis pla Ma erials Co. L d.) as mi ed i h 5 μl of a oben ene-con aining Beam 1205 LC (Beam Co.). Non-is omeri ing FLCCs (pro ocol 2) ili ed for s rface-enabled op ical defec pa erning ere based on s ing 100 μl of p re 5CB as he hos medi m, b he prepara ion pro ocol as he same o her is e. Silane-PEG capped magne ic nanopla ele s dis persed in e hanol ere hen added o he LC hile follo -ing he dis persion proced res repor ed pre io s l .[5] 5 μl of e hanol as added o 15 μl of he LC mi re o bring i o he is o ropic phase, follo ed b adding 15 μl of 0.5 1 . % magne ic pla ele s dis persed in e hanol. The s ample as kep a 90 °C for 3 h o f ll e apora e he e hanol, ielding an e cellen dis persion in he is o ropic phase a ero eld, and hen as rapidl cooled o he nema ic phase of he mi re hile igoro s l s irring. The res ing FLCC as cen rif ged a 2000 rpm for 5 min o remo e resid al aggrega ions s o ha he nal compos i e con ained onl ell-dis persed pla ele s . The nal frac ion of magne ic pla ele s in he LC as aried i hin 0.05 0.1 . %, as de ermined based on abs orbance and magne i a ion al es . Nanopla ele s e hibi ed s pon ane-o s alignmen i h large-area faces or hogonal o **n**(**r**) and magne ic momen s along **n**(**r**), as con rmed b meas ring polari a ion-dependen abs orbance[16] and probing res pons e of heir dil e dis persions o magne ic elds . Dis persions of fer-romagne ic pla ele s in he LC mi re ere s able a all s ed elds (p o 20 mT) e hibi ing a facile res pons e alread a elds belo 1 mT. Homeo ropic glass cells i h pol domain FLCCs and **M** poin ing in one of he o an i-parallel direc-ions along he er ical far- eld direc or $\mathbf{n}_0$ ere prepared s ing 1- or 0.17-mm hick glass pla es rea ed i h an aq e-o s s ol ion of 0.1 . % N,N-dime h l-N-oc adec l-3-ami-noprop l- rime ho s il l chloride (DMOAP, Acros Organics) ia dip-coa ing. The cell gap hickness of 30 μm or 60 μm as s e b in ers pacing he glass pla es a heir edges i h UV-c rable op ical adhes i e (NOA-65, Norland Prod c s) or epo con aining s ilica s pacers of corres ponding diame ers . Cell lling as done a room empera re s ing capillar ac ion. FLCC cells e hibi s pon aneo s forma ion of random magne ic domains of la eral dimens ions picall compara-ble or s ome ha larger han he cell hickness and dependen on he ini iali a ion eld of 10 35 mT (Refs . 4 and 16) (Fig. 1

he orien a ion of **M**(**r**) ips o an opposi e in-plane orien a-ion, as depic ed in Fig. 3(b), al ho gh **n**(**r**) s as con in os (Fig. 3(a)) becas e half-in eger defecs are allo ed in he **n**(**r**) line eld b no in he **M**(**r**) ec or eld.

Al ho gh, in principle, s im l aneos pa erning of bo h **M**(**r**) and **n**(**r**) can be achie ed b combining he o approaches described abo e, i is in eres ing o no e he e ol - ion of domains r c res in **M**(**r**) hen onl he direc or is pa erned (Fig. 4). The **M**(**r**) i hin magne ic domains in he pa erned region follo s hes pa iall ar ing **n**(**r**) i hin he magne ic domains and beha es discon in os l (ipping o opposi e domains) a he in er-domain alls. A applied magne ic elds, he pol domain na re of he FLCC in erplas i h he opologicall req ired all connec ing he half-in eger defec lines in **n**(**r**), cas ing a comple pa ern of domains and all defecs in ers pacing hem, hich s lo l e ol e i h ime and s rongl depend on bo h he direc ion and s reng h of **B**. In eres ingl , he id h of all defecs i hin he regions of dis or ed **n**(**r**) is of en larger han ha in regions of niform direc or (Fig. 4). To nco er he na re of magne ic in er-domain alls in he FLCCs, e s ed dark eld microscop obs er a ions ha re eal bo h loca ions and orien-a ions of indi id al nanopla ele s (S pplemen ar ideo S1)[22] a ero eld and hen **B** a differen orien a ions, s elec i el s i ches he domains of opposi e **M**. Unlike in con en ional magne ic s s ems, here magne ic domains are picall s epara ed b he s o-called Bloch or Néel alls[8] i h con in -os albei locali ed s oli onic deforma ions of **M**(**r**), magne - i a ion a he in er-domain alls of he FLCCs is no de ned, s o ha he are s ing lar in na re. This is becas e **M**(**r**) and **n**(**r**) are s rongl co pled s o ha he s oli onic deforma ions of **M**(**r**) be een he domains o ld be cos l in erms of he corres ponding elas ic deforma ions of **n**(**r**). Ins ead, he do-main alls in he FLCC ha e niform direc or b nde ned **M**(**r**), s o ha here is no as s ocia ed elas ic free energ cos d e os ch alls. A applied elds, he in er-domain alls can be par iall depri ed of nanopar icles (S pplemen ar ideo S1) and ranging in id h from he a erage s pacing be een indi id al nanopar icles o $\sim 1\mu$m, as de ermined b colloidal in erac ions be een nanopla ele s i h differen l orien ed dipole momen s of he neighboring domains of oppo-s i e **M**$\|$**n**$_0$. When **n**(**r**) $\|$**M**(**r**) i hin he domains is dis or ed, his in erpla is f r her al ered b he energe ic cos of elas ic dis or ions (Fig. 4). Al ho gh he domain all defecs in he FLCCs are s ing lar in **M**(**r**)8.12.148760TFI(96)49/F3)1T8.4876)0(l)1327(l)

and Y. Zhang. This research as s ppor ed b he NSF gran DMR-1420736. A.J.H. and I.I.S. ackno ledge he AFSOR fac l fellos hip and he hos pi ali of he Air Force Res earch Labora or d ring he ime hen his ork as nder prepara ion for p blica ion.

[1]P. Po lin, H. S ark, T. C. L bens k , and D. A. Wei , Science **275**, 1770 (1997).
[2]C. P. Lapoin e, T. G. Mas on, and I. I. Smal kh, Science **326**, 1083 (2009).
[3]Q. Li , Y. C i, D. Gardner, X. Li, S. He, and I. I. Smal kh, Nano Le . **10**, 1347 (2010).
[4]A. Mer elj, D. Lis jak, M. Drofenik, and M. Čopič, Na re **504**, 237 (2013).
[5]Q. Li , Y. Y an, and I. I. Smal kh, Nano Le . **14**, 4071 (2014).
[6]Q. Li , B. Sen k, J. Tang, T. Lee, J. Qian, S. He, and I. I. Smal kh, Phs . Re . Le . **109**, 088301 (2012).
[7]A. Mer elj, N. Os erman, D. Lis jak, and M. Čopič, Sof Ma er **10**, 9065 (2014).
[8]P. M. Chaikin and T. C. L bens k , *P c s C d s d Ma P s cs* (Cambridge Uni ers i Press , Cambridge, 1995).
[9]M. Schad , H. Seiberle, and A. Schs er, Na re **381**, 212 (1996).
[10]K. Ichim ra, Chem. Re . **100**, 1847 (2000).
[11]A. Mar ine , H. C. Mireles , and I. I. Smal kh, Proc. Na l. Acad. Sci. U.S.A. **108**, 20891 (2011).
[12]T. H. Ware, M. E. McConne , J. J. Wie, V. P. Tondiglia, and T. J. Whi e, Science **347**, 982 (2015).
[13]U. A. Hro h k, S. V. Serak, N. V. Tabir an, and T. J. B nning, Ad . Ma er. **19**, 3244 (2007).
[14]M. E. McConne , A. Mar ine , V. P. Tondiglia, K. M. Lee, D. Langle , I. I. Smal kh, and T. J. Whi e, Ad . Ma er. **25**, 5880 (2013).
[15]D. Lis jak and M. Drofenik. Crs . Gro h Des . **12**, 5174 (2012).
[16]